Primary Accretion in the Protoplanetary Nebula

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One of the major unsolved problems regarding the origin of planetary systems is the process by which the first sizeable objects (comets, asteroids, etc.) formed from solids that entered the protoplanetary nebula as micron-sized dust grains. Until recently there was little or no theoretical understanding of the key processes that characterize this epoch. The focus at Ames Research Center has recently been on three-dimensional (3-D) direct numerical simulations of particles in turbulence. Previously, it has been shown that the size of particles most strongly concentrated (by orders of magnitude) is in good agreement with the millimeter-size, molten "chondrules" which dominate primitive meteorites—and which show evidence for aerodynamic sorting which has never been explained before.

In FY97, numerical predictions were obtained of the size distribution of particles residing within densely concentrated zones in 3-D turbulence—zones thought to possibly represent the first stage of planetesimal accretion. The code can handle Taylor microscale Reynolds numbers as high as 140 (Reynolds number as high as 1300), and it can handle a million particles at each of 16 Stokes numbers simultaneously (the Stokes number is the ratio of particle stopping time to the Kolmogorov eddy turnover time, and is proportional to the particle radius and density). To test the models, a study was completed in which primitive meteorites were disaggregated and the size distribution of their chondrules was measured directly. The data so obtained are far superior to similar data obtained by examining slices of rock in a microscope, because the slicing process can bias size estimates. These new results also provide direct determination of the chondrule density, which is unattainable in any other way. Finally, these results provide the best measurements yet of the volume of fine-grained dust rims that surround many chondrules—generally believed to have been acquired by sweep-up of fine dust from the nebula gas.

Comparison of measurements and theoretical predictions has been very encouraging. The first figure shows a comparison of model predictions with the actual relative abundance of chondrules, as a
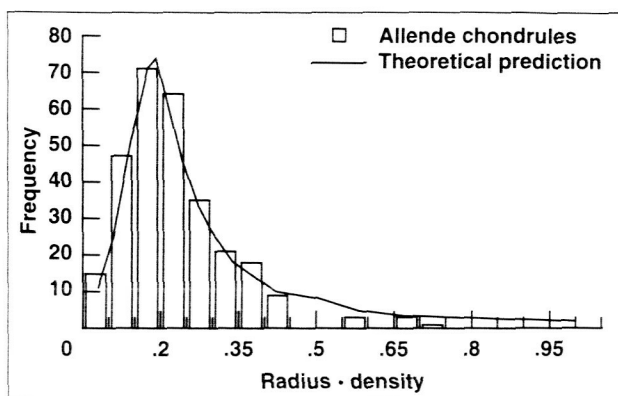

Fig. 1. Comparison of theoretical predictions for the size distribution of particles within a dense clump (smooth curve), proposed as the precursor of primitive meteorite parent bodies, with the observed size distribution of disaggregated chondrules (histogram). Similarly good agreement is found with data obtained by another group for a different kind of meteorite.

function of the product of their radius and density (the primary determinants of the Stokes number). The data and the predictions are normalized together at their peaks, and the shapes agree very well. The asymmetry of the theoretical prediction is a natural outgrowth of the model, if a binning volume of one Kolmogorov eddy scale on a side is adopted as proposed. Comparably good fits are found with data from a different team on a different meteorite.

The discovery at Ames (FY96) of the multifractal nature of the particle density field connects the particle concentration process with the same cascade process that partitions the dissipation of turbulent kinetic energy. The scaling properties of cascade processes can then be used to make reliable predictions of various particle-density-related quantities under nebula conditions. The second figure shows the volume having concentration factor C (C is the ratio of local particle density to the mean). The "data" are binned from simulations at three Taylor microscale Reynolds numbers, and the "models" are parameterized only by Reynolds number (once the Reynolds-number-independent
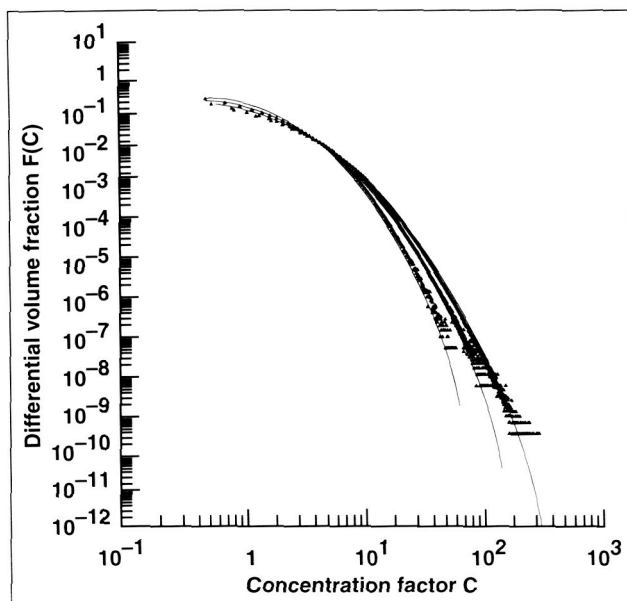
Fig. 2. Comparison of theoretical predictions of volume per unit volume occupied by particles with concentration factor C (lines) with actual binned probability distribution functions. The predictions used only the single fractal descriptor known as the singularity spectrum, which was defined by averaging over data at all three Reynolds numbers. The multi-fractal approach makes very good predictions of this and other quantities related to the particle-density field.

"singularity spectrum" is determined from the fractal properties of the data). The agreement is very good.

Using this formulation for the nebula, it is predicted that there will be about one clump with a typical dimension of a few kilometers on a side, with a concentration factor of 10^5 to 10^6, for every volume that is 10^4 (1 followed by 4 zeros) kilometers on a side. There will be numerous such clumps in the nebula region of interest, 10^7 kilometers thick and 10^8–10^9 kilometers wide (and even more common concentrations of lower degree). The multifractal formalism is thought to be a fundamental advance in two-phase fluid dynamics; it will be extremely useful in quantitatively describing the properties of selectively concentrated particles in turbulence. For instance, the expected encounter times for chondrules with clumps sufficiently dense to remove the chondrule from circulation, and collision rates within such clumps which augment sticking and accumulation of particles, can also be calculated.

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Telltale Electric Currents During Impacts on Rocks

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Impact studies lead to new insights into geophysical phenomena ranging from electric signals accompanying earthquakes to magnetic signatures of past meteorite impacts on Earth, the Moon, and Mars.

Dry rocks, in particular dry igneous rocks, are known to be good insulators, meaning that they are unable to generate and to transport sizable electric currents. However, evidence has accumulated over the past few years that there is something special about the traces of "water" (H_2O) which nominally anhydrous minerals, the main constituents of igneous rocks, incorporate into their crystal structures when solidifying from water-laden magmas. When water molecules enter a mineral structure, they usually turn into hydroxyls, $H_2O + Si/^O\backslash Si = Si/^{OH}\ _{HO}/Si$, but the hydroxyls reshuffle their electrons in such a way that a hydrogen molecule and a peroxy link, $Si/^{OO}\backslash Si$, are formed for each hydroxyl pair.

Since all igneous rocks on Earth and presumably on Mars solidified from water-laden magmas, the presence of peroxy links deserves attention because, when peroxy links can break apart, they generate electric charges. These charges are defect electrons, also known as "positive holes," similar to the holes in semiconductors which are necessary, together with electrons, to build a transistor. Peroxy links dissociate upon heating, but it has now been recognized that they also break apart when subjected to a sudden